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Post-mortem estimation of temperature distribution on a power transformer: Physicochemical and mechanical approaches

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HIGHLIGHTS

- New post-mortem methodology to estimate temperature in power transformers coils.
- Comparison with methodology based on degree of polymerization of dielectric paper.
- The tensile strength based method provides faster and more repeatable results.

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ABSTRACT

Power transformers are electrical machines that allow us to transport electric energy, with reduced losses, from generation stations to consumption points. This definition gives us an idea of the number of transformers that are used in power distribution systems worldwide. The main problem that may affect power transformers is the operation at high temperature. This paper summarizes the results of a postmortem temperature estimation carried out on an 800 kVA distribution transformer. Two methodologies are considered for estimating the temperature distribution in the windings of the machine. The first is based on the calculation of the degree of polymerization and the second is obtained from the tensile strength index. By knowing the value of these two magnitudes for a new and for an aged paper, and the period of operation of a transformer, the temperature distribution along the height of the windings can be estimated. None other previous works have used the tensile strength of winding paper for temperature distribution estimation. With these results and the loading regime records, similar transformers still in operation can be operated in an alternative manner and future designs can be improved.

1. Introduction

Transformers are one of the most expensive and critical components of electric energy transmission and generation systems [1]. Although transformers are very reliable machines a failure is possible at any age due to many factors as incorrect specification or operation, design or manufacturing errors, bad maintenance, excessive ageing … [2]. In this way, there is a working group (WG A2.45) within the International Council on Large Electric Systems (CIGRE) called “Transformer failure investigation and post-mortem analysis”. They began to work in 2011 and at the end of 2014 aims to publish a report with first conclusions [3].

Therefore knowing transformers condition is essential to manage large networks. The temperature of isolation is a critical parameter affecting correct performance of these machines because high temperatures degrade dielectric materials, oil and paper, shortening their lifespan [4,5]. In this line, several thermal studies about power transformers have been published in last decade. Their approaches are based on the solution of the differential equations governing heat transfer phenomena. The main goal of practically all these papers is the determination of the dielectric oil velocity and temperature profiles inside transformers' windings.

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A 2D-model of a pass of a Low Voltage Winding (LVW) that belongs to a 3-phase disc-type transformer was simulated by Torriano et al., in 2010, thus obtaining the effect of the model accuracy, the mass flow rate and inlet boundary conditions on the flow and temperature profiles. They also determined the location of the hot-spots in the winding [6].

In 2011, Gastelurrutia et al. presented slices of several ONAN distribution transformers (2D-models) in which the oil flow and the thermal distributions were numerically calculated, thus allowing the comparison of the results with the experimental ones [7]. In this year, the same authors published [8] a zonal model representing the cooling of distribution transformers. The objective was to predict the top oil temperature. Reasonable errors with respect to experimental measurements of top oil temperature were obtained with this methodology.

More recently, in 2012, Torriano et al. carried out a comparison between 2D and 3D models of the same geometry, thus determining the existence of three-dimensional fluid flow phenomena that cannot be obviated such as it occurs in the 2D-model [9]. This year, Skillen et al. developed a 2D-model based on the geometry of Torriano's transformer with five passes in a column. The presence of hot-plumes in some horizontal ducts and the transmission of hot streaks from one pass to the next (flow coupling) were the main conclusions of this paper [10].

Smolka published in 2013 [11] an optimal mutual configuration of coils and cooling ducts for the effective cooling of a dry-type transformer. For this he used two tools, computational fluid dynamics (CFD) and genetic algorithms, on real 3-D transformer geometry. The results show that the non-uniform positioning of the wires and air ducts and an optimal splitting of high- and low-voltage coils can significantly lower the hot-spot temperature and improve the heat dissipation in comparison with current transformer designs. In this year it was also published another article [12] which modelled the ventilation by natural convection of two underground transformer substations. The air flow pattern and the air temperature distributions inside the substation were analyzed, proposing correlations between air mass flow rate and heat transfer coefficients.

A new approach to the ventilation of underground transformer substations was published in 2014 [13]. Beiza et al. proposed an algebraic thermal zonal model during a standardized temperature rise test. They showed that the main parameters affecting the ventilation of the substations are the pass area between the LV–MV zone and the transformer zone, the surface area of the ventilation grilles in the substation with horizontal ventilation, and the perimeter of the protruding ventilation vents in the substation with vertical ventilation. Finally, also in 2014, Yatsevsky [14] simulated heat transfer and oil flow in cooling channels of oil-filled power transformers with multicoil windings. The results showed the distribution of heat transfer coefficients and radial component of velocities along the different channels, considering a natural cooling system.

On the other hand, the aim of this article is similar to the previous ones, to know the distribution of temperatures inside a transformer; however, the dielectric paper condition is used for determining these temperatures along their windings. The primary solid insulation used in liquid filled power transformers is cellulose. The cellulose which is composed of polymerized glucose molecules suffers degradation due to thermal stress caused by electric load losses in the transformer, moisture, oxygen, contamination from conducting particles and mechanical damage or weakening from vibration [4,5].

Different authors have carried out post-mortem analysis, obtaining from paper samples the degree of polymerisation (DP), which is a valid indicator of paper ageing [15–17]. These studies must be performed once the transformer has been removed from service. The combination of the results from service history and post-mortem analysis from scrapped and failed transformers help to discover design and material problems specific to a family of transformers which were designed for a specific application and have the same size, voltage class, winding style and cooling system.

For instance, Susa et al. carried out the condition assessment of a generator transformer by the mapping of degree of polymerization (DP). They also showed the temperature mapping, where the temperature estimation was based on the paper ageing kinetics, transformer loading and insulation operating history. They used a model where the rate at which the bonds break was considered constant. Finally, they gave a new equation for the relative ageing rate considering all insulation conditions providing possibility of counting transformer loss-of-life more accurately [15]. Other situation where accurate paper degradation diagnostic could be useful was described by Martins et al. [16]. At the end of 2007, and after a network rearrangement in a region of Portugal, the Pracana substation became redundant. These authors performed a condition evaluation of a transformer to make a decision regarding its transfer to a new substation located in the same region. They carried out a diagnostic based on oil analysis and measures of DP and compared them. Leibfried et al. investigated new approaches to determine water in oil-paper-insulated power transformers to conform diagnostic parameters to post-mortem investigations as well as, correlations between the furan (2-FAL) concentration in the oil and the average DP [17].

All these post-mortem studies have been based on DP which constitutes one of the most important parameters for the evaluation of insulation condition. However, there is not any other published article that has used the tensile strength index (TS) to conduct a post-mortem study so far, although this parameter allows also the analysis of dielectric paper ageing. In Refs. [18,19] the authors studied the evolution of TS and DP, versus time, but none of them established a model of ageing that defines the relationship between DP and TS. Only in Ref. [20] an expression that correlates DP and TS with time and temperature was presented.

The approach shown here is a case study which has adapted an existing model used to predict the values of TS and DP after an ageing time at a certain temperature in the laboratory [20]. However, this model is used here in an alternative way for post-mortem analysis. The objective is to estimate temperature distributions considering the machine life span and the DP and TS values of new and aged paper.

2. Experimental methodology and calculation

This work has followed the methodology shown in Fig. 1. Paper samples were taken from a failed distribution transformer to determine DP and TS. Later, the temperature distributions were obtained based on DP and TS results. And finally, these temperature distributions were compared in order to show the suitability of tensile analysis for post-mortem studies.

2.1. Samples collection

Paper samples have to be taken at different heights in order to calculate the tensile index and the degree of polymerization. This allowed us to observe the degradation distribution along the coils. Generally, the dielectric paper for insulating the phases is composed of two or more layers, so paper samples have to be taken from all the layers to test their real state. All samples have to be